
SOLAR POWER PLANTS AND THEIR APPLICATION

Solar Stirling Engine Rig Tests

I. A. Tursunbaev, E. P. Orda, A. I. Lezhebokov, A. P. Korobkov, and A. I. Semyannikov

Physics of the Sun Scientific Production Association, Uzbek Academy of Sciences, Tashkent, Uzbekistan

Received June 3, 2010

Abstract—A description of a prototype four-cylinder Stirling engine construction with the heat receiver of the concentrated solar radiant flux and with a swashplate drive is given. The rig tests have been carried out in an effort to optimize the individual engine units. They have been conducted in the cooling system mode and in the mode of an engine working with a natural gas combustor. The findings are analyzed, and means to increase engine efficiency are given.

DOI: 10.3103/S0003701X10030047

The solar Stirling engine (SE) with 5 kW power is developed as an electricity-generating construction unit of a solar modular power system with a mirror concentrator of solar radiation and as a high-temperature heat source.

The SE is a four-cylinder double-acting Stirling engine of α modification, the longitudinal axis of symmetry of which coincides with the optical axis of the concentrating system. A moving piston dividing the cylinder area into hot and cold chambers with variable volume is located in each cylinder. Each hot chamber is connected with the cold chamber of the next cylinder via a heater, regenerator, and cooler.

The motion of the SE pistons and compressor piston is performed by the swashplate drive. The shaft rotation axis coincides with the engine's longitudinal axis of symmetry. The electric generator embedded in the engine crankcase is placed on the shaft. Furthermore, the oil pump of the lubrication system is geared by the shaft.

The solar receiver is combined with the SE heaters and is equipped with water-cooled protective diaphragms with an entrance gate 110 mm in diameter. Diaphragm protects the external engine system elements from the concentrated solar radiant flux in the process of Sun-tracking by solar power plants and in case of the tracking system troubles. In addition, it utilizes convective heat losses from the heat receiver's chamber.

Figure 1 presents the schematic longitudinal section of the SE. Structurally, the SE is comprised of three blocks.

(1) The heat-exchanger block, including heaters consisting of two chains of tubes 5 mm in diameter that form the cylinder chamber of the heat receiver, regenerators, and coolers in basic frames and four sleeve cylinders. The block is positioned in the basic flanged frame, through which it interfaces with the crankcase.

(2) The crankcase, incorporating a lidded frame, a swashplate drive, a rotating oil pump, a compressor with a receiver, and four cylinders with slippers and packing assemblies of piston plungers. An oil tank, an oil cooler, and a compressor receiver with an oil filter are located within the crankcase.

(3) The electric generator with a water-cooled enclosure and with a lid containing sealed electric leads for connection to the three-phase network. The electric generator is a rotor of the standard three-phase induction motor with 5-kW power rigidly mounted on the SE shaft and a stator mounted in the frame body with a water-cooled enclosure. The electric generator is also used as a starter, and, upon reaching a nominal rotation frequency, it switches to the generator mode.

The force lubrication system is used for lubricating the crosshead mechanism, bearings, plunger balls, and other contacting pairs of the drive mechanism. The oil is directed to the cooler with a rotating oil pump united with the main shaft. Then the oil flows to the friction assemblies and next gravitates to the crankcase and the oil tank. The oil is pumped out of the tank with the rotating oil pump.

A compressor with receiver maintains the medium pressure in working chambers at a level of 10 MPa with a working body pressure in the crankcase of 2.5–3.0 MPa. The compressor drive is realized by the swashplate, much as is the SE pistons' drive.

The SE cooling system represents a direct cycle after-cooling system; it is provided with cooling water from an external water-supply source with a mass flow no less than 250 g/s at the hydraulic drop 0.2–0.25 MPa. The connection scheme of the engine cooling units is as follows. First, water is carried to the coolers. Then, the cylinders are flowed over. Next, the cooling water flow is delivered to the generator enclosure, the oil cooler, and the heat receiver diaphragm.

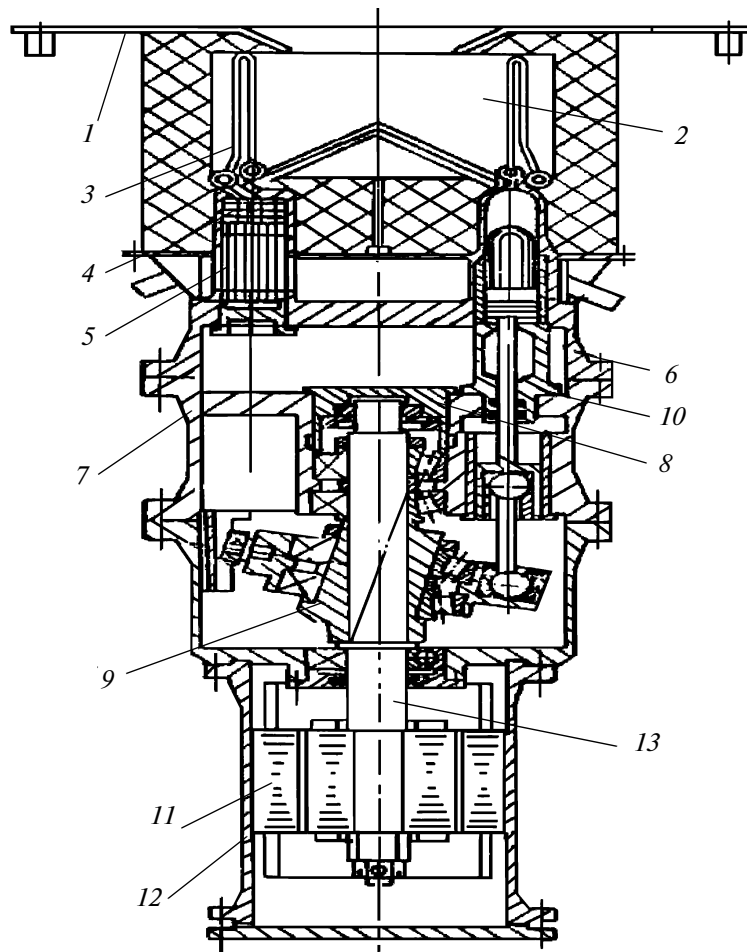


Fig. 1. Solar Stirling engine with 5-kW power. (1) water-cooled diaphragm; (2) heat receiver's chamber with conical baffle; (3) heater tubes; (4) regenerator; (5) cycle cooler; (6) heat-exchanger frame; (7) crankcase; (8) oil pump; (9) swashplate drive; (10) plunger packing assembly; (11) electric generator; (12) lidded frame of the electric generator; (13) driving shaft.

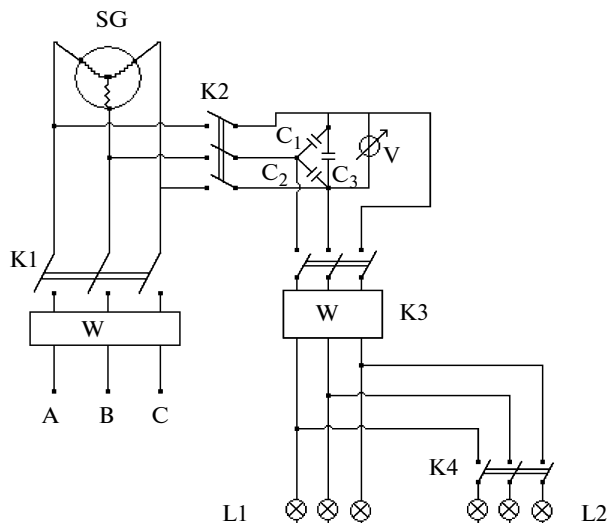


Fig. 2. Electrical connection scheme. SG, starter-generator; K1, starter actuator; K2, generator excitation actuator; K3, load actuator; H1, starter-generator work indication; C_1 – C_3 , excitation capacitors; A, B, C, three-phase chain terminals; V, voltmeter; W, three-phase meter (10 A); L, load. Capacity $C_1 = C_2 = C_3 = 40 \mu\text{F}$, $\geq 500 \text{ V}$.

The hot water from the cooling system goes to the storage tank and then to the system of the hot water supply of the load.

In order to optimize the main engine units and systems, SE rig tests were conducted in the cooling mode with the drive from the starter-electric generator and in the engine mode with heat supply from the natural gas burner.

Figure 2 presents the electrical connection scheme of the test bench.

In the cooling mode, the electric generator was used as an engine, gearing the drive mechanism and piston system with a frequency of $\sim 1500 \text{ rpm}$. A temperature of -100°C was attained in the SE expansion chambers under a pressure of 4–5 bar in the crankcase. This confirms the correctness of the assembly and of the four functioning SE circuits.

Rig tests in the engine mode were conducted using a natural gas combustor. The SE was idling without load with helium pressure in the crankcase of 15 bar. The heater tubes' temperature was 650 – 720°C . The

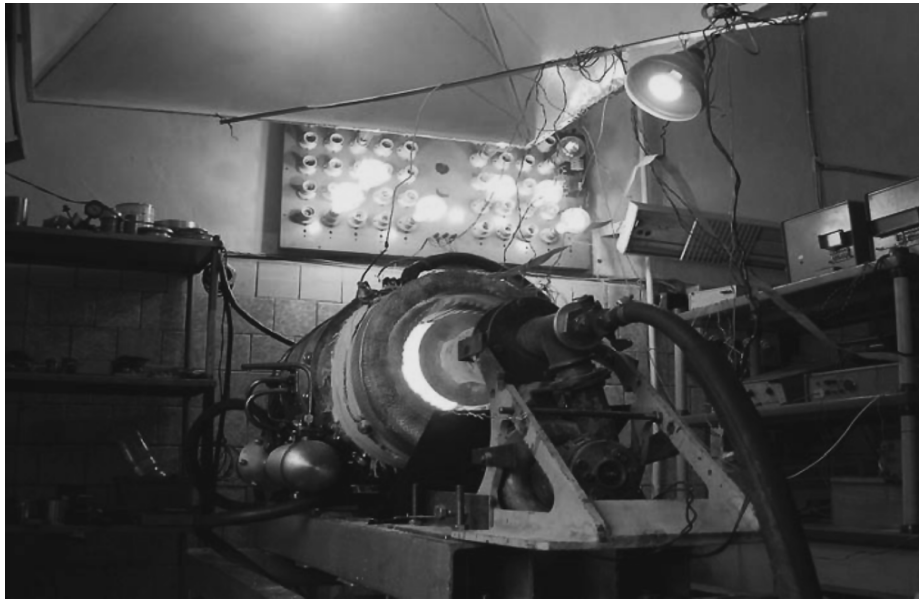


Fig. 3. Test of engine with natural gas burner.

medium pressure in the working chambers after the compressor amounted to 70 bar. The frequency of the SE shaft rotation ran to 1400–1600 rpm. After final adjustments in some units of the drive mechanism, tests were continued in an effort to obtain the SE's nominal parameters.

Figure 3 presents the test bench engine with a natural gas burner from a domestic gas supply system (gas pressure is 0.002–0.004 MPa).

An oscillograph of pressure transducer readings in the engine working chamber during the tests with a medium pressure of 87 bar in the working chambers is illustrated in Fig. 4. The maximal pressure in the pro-

cess came to 103.5 bar, and the minimal pressure amounted to 70 bar.

In the course of the rig tests, there were more than 40 hot starts (pressure generation mode) with the aim of detecting and investigating the inadequacy level of the design models and techniques and engineering and technological errors in manufacturing of the parts and SE units.

The key data in defining the degree of conformity of design characteristics to the real SE parameters are listed in table (design parameters are worked out by the procedure of [1]).

As a result of the test, a range of design and technological drawbacks were discovered that did not allow

Table

Parameter name	Unit of measurement	Actual/design value
SE power, N_{el}	kW	2.5/5
SE efficiency, η_{SE}	%	15/25
Combustion chamber (CC) efficiency, η_{CC}	%	55/55
CC heat capacity, $N_{cc} = N_{el}/(\eta_{CC} \eta_{SE})$	kW	30/36
Domestic hot water (60–80°C) heat capacity (without considering use of the combustion chamber exhaust)	kW	15/16

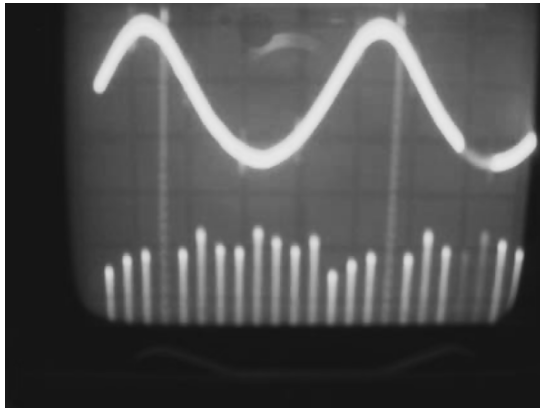


Fig. 4. Oscillograph of pressure changes in one of the SE engine chambers.

realizing the design parameters; in particular, the 2.5-kW pressure obtained constituted 50% of the design value. The test data are presented in Fig. 5 as the generated electric power dependence of the medium pressure in the engine working chambers.

The test data show that it is necessary to develop SE construction further, to bring its parameters up to the design ones, and to increase its manufacturability, effectiveness, and safety in the working process both with gas fuel and concentrated solar radiant flux.

Such activities include the following stages:

(1) improving piston and plunger packings in order to acquire maximum effective pressure with minimum mechanical losses;

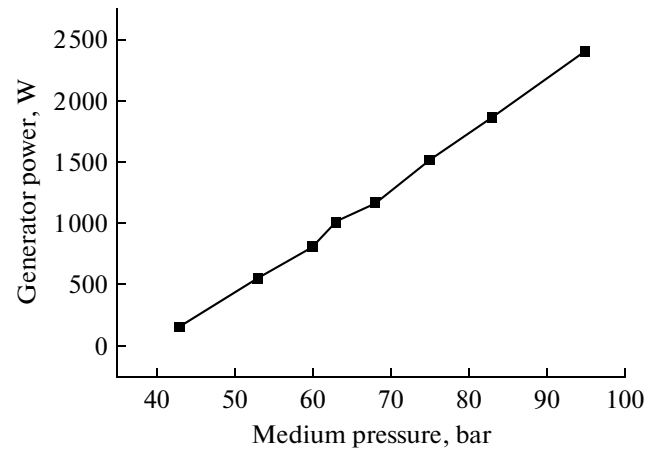


Fig. 5. The test data of the SE in the engine mode.

(2) increasing the working effectiveness of the heat-exchanger block by decreasing hydraulic losses and heat exchange enhancement;

(3) developing the pumping system of the working body into the engine working chambers in an effort to increase the indicator work of the cycle; and

(4) optimizing the heat supply system from the solar concentrator and gas burner.

REFERENCES

1. Tursunbaev, I.A., Analytic Model of Solar Power Plant with a Stirling Engine, *Geliotekhn.*, 2007, no. 1, pp. 21–26 [*Appl. Sol. Energy* (Engl. Transl.), 2007, vol. 43, no. 1, p. 13].